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ANALYSIS OF THE INFLUENCE OF FRICTION STIR PROCESSING ON GAS TUNGSTEN ARC WELDING OF 2024 ALUMINUM ALLOY WELD ZONE

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ABSTRACT

Gas tungsten arc welding is the most commonly used process for joining of AA 2024 alloys, which are highly demanded in aircraft structural applications. The quality of the welds and strength of the welded joints achieved using this process, the weld fusion zone of this alloys usually exhibit the columnar grains, which are coarser than the substrate, due to the persisting thermal conditions when the fusion zone starts to solidify. This kind thermal attribution often causes to degrade the strength of the weld metal and lead to impair its resistance to sustain the hot cracking issues. In addition, there are some unavoidable micro structural defects formations such as porosity and micro cracks in the fusion zone. The formation of these defects at the top of the fusion zone will result in the reduction of weld strength about to half of the base metal strength. The present study will focus on the improvement of micro structural and mechanical properties of the gas tungsten arc welded 2024 aluminium alloys using a novel approach of friction stir processing procedures. In order to overcome these issues, the top surfaces of the gas tungsten arc welds are processed using friction stir processing up to certain depth from the top of the welds. The weld metal micro structural characterization studies revealed that the friction stir processing was controlled or decreased the amount of porosities and micro cracks formation. In addition, it destroyed the coarse grains dendritic structure in the weld zone and helped to dissolves the precipitates of secondary particles, which exists along the grain boundaries. The changes in the weld microstructures and grain refinement significantly improved the hardness of the friction stir processed welds over the base metal and gas tungsten arc welds. The mechanical properties also significantly changed along with the quality of the weldments. In addition, the formation of very fine precipitates is observed in stir zone due to the effect of intense plastic deformation and temperatures during friction stir processing.

KEYWORDS: Gas Tungsten Arc Welding, 2024 Aluminium Alloy, Friction Stir Process, Microstructure, Mechanical Properties.

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Original Article

INTRODUCTION

In recent years, non-ferrous materials which has high strength to low weight properties have substantial consideration in aerospace, automotive industries, ship building and cryogenic application to enhance the fuel efficiency in transportation industry and moderate the environmental issues [1-3]. Moreover, the weight of the structures can be reduced with the fabrication of different products to obtain the several advantages of the aluminum alloys. However, the joining of aluminum alloys has incessantly denoted a great challenge for manufacturing engineers. In particular, the heat treatable aluminum alloys such as 2024 alloy and its combination

to other materials is difficult to fabricate using conventional fusion welding methods [4-7]. The weldments after fusion welding resulted in formation of some welding defects like porosity, micro cracks in fusion zone during the weld pool solidification from the molten state to solid state. Also, there are lots of other difficulties are consorted to this type of joining methods, in particular these are associated with presence of persistent oxide layer, solidification shrinkage, thermal expansion, high thermal conductivity and high solubility of hydrogen and other gases in the weld pool [8-10]. In addition, the conventional methods often caused to deteriorate the joint strength due to the occurrence of softening effect and significant phase transformations in the weldment [11-14]. With the considerations of all these aspects, lead the aluminum alloys especially the 2024 alloys usage continuously increasing demand in aeronautics applications for the reliable mechanical strength of the joints. However, the additional problems arise when the corrosion resistance properties are highly required: for this instance, the phase transformations persuaded in the fusion zone or in alloy structure often ensue into mysterious modifications of the material properties [15-17].

There are several techniques applied such as heat treatment processes, gas tungsten arc welding (GTAW) arc melting and mechanical deformation process to modify the materials properties in order to improve the joint properties. However, these methods are not efficient and some of those are not applicable for using welded joints, where the joint strength is highly required. Most recently, friction stir welding (FSW) become a prominent welding process for joining of aluminum alloys, which was invented by The Welding Institute (TWI) in 1991 [18, 19]. Friction stir welding process is a solid-state welding method that can make high quality joint considerably with the low cost of heat treatable aluminum alloys. The joining of aluminum alloys such as 2xxx and 7xxx series alloys which are considered as unweldable are can be easily weld by using FSW process. Moreover, it is also suitable for joining of dissimilar materials like friction welding, diffusion bonding and roll bonding processes [20-26].

FSW technique involves a cylindrical rotating tool of non-consumable material that plunges into the two plates and moves between the butt seam, stirs, and bonded them together without melting of the welded metal. The heat is produced during FSW process and generation of thermo-mechanical conditions develops a heterogeneous fine-grained microstructure across the weld seam. The further improvements in FSW process later years resulted in development of a friction stir processing (FSP) procedure. FSP is also like a FSW process that can produce a severe plastic deformation in the weldments and used as a collective tool for the surface and microstructural modifications of various materials and aluminum alloys [27]. FSP has several advantages over the other metal working processes, such as improving the microstructural formation by refining the grain size, its densification and homogeneity of gain distribution in a single pass. The microstructures and mechanical properties of the weld metals can be easily controllable by adjusting or optimizing of process conditions and FSP is efficient technique for surface modifications [6]. In particular, FSP of the as-cast alloys exhibits a wide range of grain refinement, destroying and dissolution of the precipitates and avoid the porosity in the weldments; thereby it putting up an appealing ductility, strength and crack free weld microstructures.

In the present study, a novel approach was used for 2024 aluminum alloy of GTAW welds by applying FSP procedure to enhance the microstructural development and mechanical properties. The results of the GTAW weldments consisting of porosity and micro cracks in the fusion zone, which are causes to impair the mechanical properties of the welds. In order to overcome the defects, FSP procedure was applied along the GTAW weld bead upto certain depth of the weld zone from the top surface of the welds. The resultant welds were studied in detail to characterize the microstructural differences, grain growth and porosity defects. Furthermore, the effect of FSP procedure on the mechanical properties of

the welds was evaluated, and is compared with the newly formed FSPed microstructural zones to understand and improve the weld metal characteristics.

EXPERIMENTAL PROCEDURE

The heat-treated aluminum alloy of 2024 material used in the present study is in the form of plates with the dimensions of 100 x 50 x 5 mm. The chemical analysis of the 2024 alloy consisted of the elements of Al (base element), Si (0.5 wt.%), Cu (3.9 wt.%), Fe (0.48 wt.%), Mn (0.58 wt.%), Mg (1.45 wt.%), Cr (0.09 wt. %), Zn (0.24 wt.%) and Ti (0.148 wt.%). The plates were cleaned with acetone to remove the oil, dirt etc., and, are brushed with steel wire brush to remove the oxide layer. Prior to the GTAW welding, samples cleaned with alcohol and dried to remove the moisture in the plates. After removal of the oxide layer, edge preparation was done for making the butt joint. The Invertec V205-T AC/DC, automatic gas tungsten arc welding machine was used for producing the GATW welded joints. The filler material of ER5356 with a diameter of 2.4 mm used for filling the butt configuration in the inert media using Argon shielding gas to protect weld pool from the dissolution of atmospheric gases.

The chemical composition of the filler wire elements contained the Al (base element), Si (0.245 wt.%), Cu (0.05 wt.%), Fe (0.41 wt.%), Mn (0.12 wt.%), Mg (0.45 wt.%), Cr (0.11 wt. %), Zn (0.09 wt.%) and Ti (0.15 wt.%). To obtain the reliable joints, GTAW welds were made based on the trial and error method to fix the welding conditions. During welding, the optimized welding conditions such as welding current of 89 A, voltage of 20 V, and the welding speed of 34 mm/min and argon shielding gas for protection are used. The GTAW weld reinforcements were removed by machining it and flatten the weld bead with its substrate sides for applying better FSP enactment. After preparation of the GTAW welds, FSP was carried out using a modified milling machine at the transverse speed of 1.1 mm/s, target depth of 2 mm, rotational speed of 1200 rpm and a vertical force of 8000 kg applied over the welds during FSP. The cylindrical, FSP tool was made of EN 31 with a pin length of 2 mm and it was heat-treated to enhance the hardness properties.

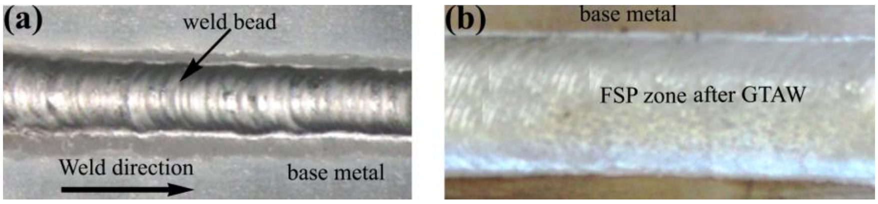

Figure 1: Micro Graph Shows of the Weld Bead Formation and Quality of the Welds of (a) GTAW and (b) GTAW and FSP Processed Joints

The pin and shoulder diameters of the FSP tool are 6 mm and 18 mm respectively. The tool was tilted at an angle of 3° to the shoulder horizontal plane to the tip of the plane to impart the better forging action. The samples of 2024 GTAW welded one and another set of samples are GTAW welded samples followed by FSP (GTAW+FSP), are shown in figure 1. These two sets (GTAW and GTAW+FSP) of samples were cut across the weld seams, and are prepared for the microstructural characterization as per the standard metallographic procedures. To reveal the microstructural features, polished samples were etched with tucker's reagent (2.5 ml H_2O, 4.5 ml HNO_3, 1.5 ml HF and 1.5 ml HCl), and followed by washing under running water and alcohol, and air dried for better visibility of the microstructures. The microstructural analysis was carried out by optical microscope (OM), and the Vicker's micro hardness tester has been used for hardness measurements across the cross section of the welds. The mechanical properties of the joints were evaluated under universal testing machine UTE-40 with a capacity of 100 kN, India. The ASTM E8 standard was used for preparing the tensile

samples. All the samples were tested at room temperature using crosshead speed of 2 mm/min. To obtain the reliable strengths, each joint was evaluated with five tensile samples, which are taken from the same joint.

RESULTS AND DISCUSSIONS

The fusion zone of the aluminum alloys during gas tungsten arc welding forms the variety of microstructures adjacent to the weld fusion line. It is well known that, during weld pool solidification an epitaxial grain nucleation occurs in the heat affected zone (HAZ) and the solidification continues in the allowable growth direction. Other than this weld pool solidification also encontered with another issues. The microstructures of the AA 2024 alloy weld metal contains lot of gas pores, as illustrated in figure 2. The reason for formation of the porosities are due to more amount of aluminum to absorb hydrogen during weld metal melting and solidification process. The solubility of hydrogen in aluminum is very high and for this instance, the possiblities of excess amount of porosity formation in the conventional arc welding of aluminum alloys is substantially high. During arc welding, the hydrogen is easily introduced unintentionally through the contaminants from the welding consumables or specimens. The porosities in the microstructures are varying in their size and number: This is might be due to the avialbility of hydrogen in the weld-metal and entrapped gas bubbles in the weld puddle [8, 28].

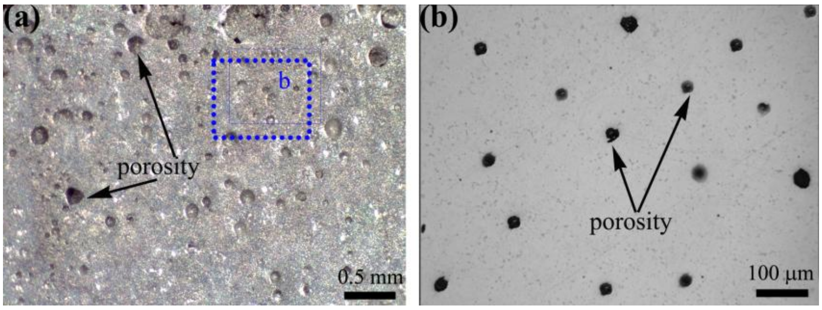

Figure 2: The Cross Section of the GTAW Welds Illustrates the (a) Macrostructure of the Welds Showing the Presence of Pores and Porosity, (b) Enlarged View of the Microstructure with the Porosity in the Weld Fusion Zone

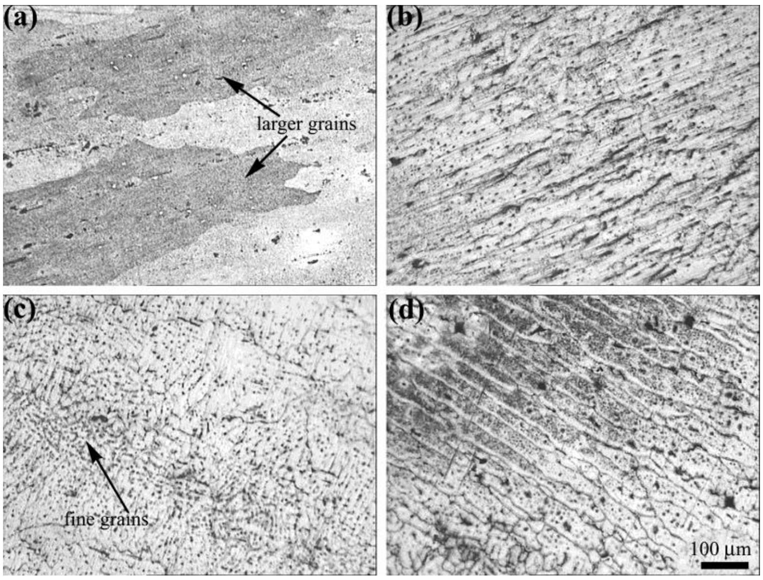

Figure 3: The Microstructures of the GTAW Welds Illustrates the Grain Size Difference and Defects Formation in the Various Zones (a) Base Metal (b) Heat Affected Zone (HAZ) (c) Fusion Zone (FZ) and (d) Partially Melted Zone (PMZ)

Figure 3 shows the microstructures of the GTAW welds with the formation of different zones. The gain size of the base metal is completely modified after welding process, and a columnar epitaxial grains can be clearly seen from the HAZ and partially melted zone (PMZ) which are formed at high temperatures adjacent to the fusion zone. In this zones, the precipitates which are parent hardended experience a heat treatment of over ageing, that can cause to phase formations from θ” → θ’, resulting in deteriorating the mechanical properties of the welds [8, 11, 28]. It is observed that the microstructures of HAZ and PMZ contain coarser and grown epitaxial dendritic grains of α-Al and θ-phases [29]. The grown dendritic grains are caused due to the cooling and solidification rate of the weld pool and the presence of Mg and other elements in the eutectic phases. However, these are not clear in the fusion zone and the fine and equiaxed grains are observed in some regions. The grain boundaries are distributed with the precipitates and only few amounts of the precipitates are observed inside the grains. The presence of insufficient amounts of Mg in weld metal resulted in the formation of weak precipitates and not enough to form intermetallic compounds. However, these can be conformed in the next section of the hardness properties of the welds. The zones of the weldments exhibited the micro cracks in the grain boundaries where the precipitates are rich in concentration and wider gap between dendrites led to defects formation.

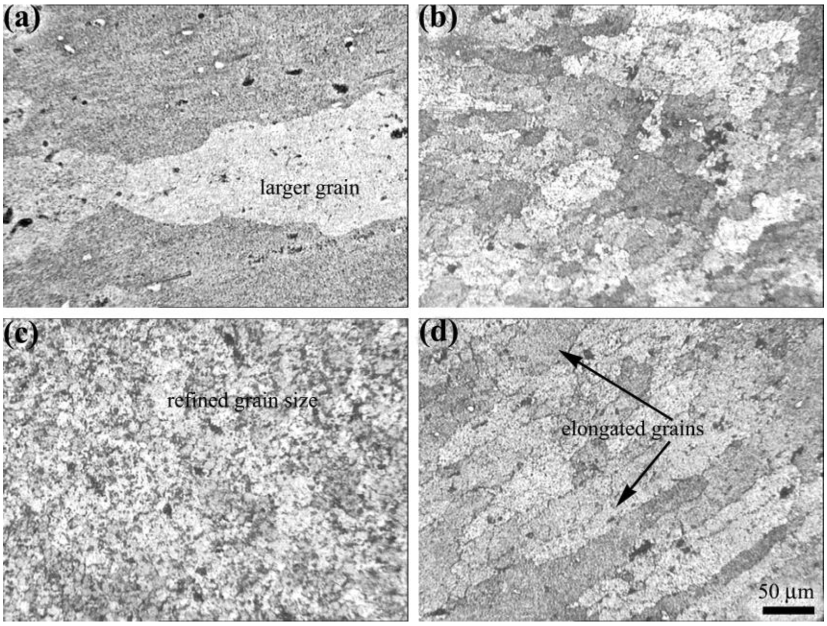

Figure 4: The Microstructures of the GTAW+FSP Welds Illustrates the Grain Refinement and Defects Formation in the Various Zones of (a) Base Metal (b) Heat Affected Zone (HAZ) (c) Stir Zone (SZ) and (d) Thermo-Mechanically Affected Zone (TMAZ)

Even though, enough precautions are taken for GTAW welding of aluminum alloys, there are still the presence of porosites in the weld zone, which resulted in the careful understanding of various sources of these contaminats to identify the cause and take the necessary actions to get rid of porosities. It is very costly and difficult to avoid porosity in GTAW process for obtaining a defects free welding process. The new approach of using FSP process over the GTAW welds resulted in a significant improvements in the weld zone. The defects free microstructures with the refined grain sizes in the weldzone are depicted in figure 4. From the microstructural observations it is found that the coarse and grown dendritic structures are completely modified in the HAZ and thermo mechanically affected zone (TMAZ), it might be due to the stirring effect of the pin and it’s influence on breaking of the dendrites and precipitates completely and refined them into a new shape formation as shown in the GTAW+FSP weld microstructures. The grain size of the stir zone (SZ) is much finer than the GTAW fusion zone and there is no evidence of porosity in the weld zone. The small size pits also hard to find

from the GTAW+FSW welds and a complete defect free welds are achived. The formation of a coarse grains and its growth direction of the TMAZ microstructure similar to the coarser grains growth and direction of PMZ.

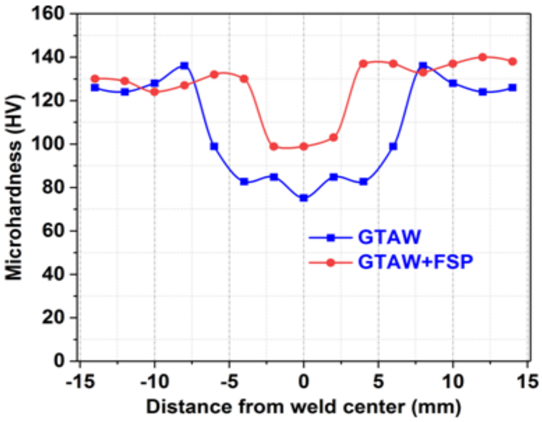

Figure 5: Micro-hardness Distribution of the Two different Welding Processes across the Weld Zones

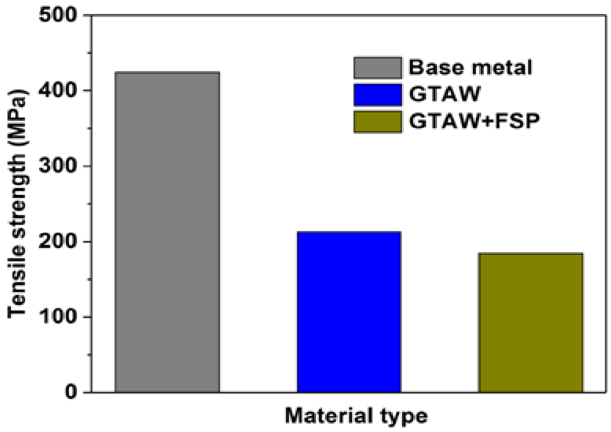

Figure 6: Tensile Strength of the Two different Welding Processes of GTAW and GTAW+FSPed Joints

The formation of precipitates are also observed across the TMAZ region in GTAW+FSP welds which are in very small size and less density. However, these may not have significant effect on the degradation of weld metal properties. On the other hand, it is worth to mention that the tool motion induceses the greater stresses thus resulted in fine grain structure formation, which can allows a partial recovery of the weld metal strength properties, and this effect can be seen only on weld nugget [30]. The distance away from the weld center towards unaffected base metal, the HAZ region after the TMAZ, in this zone the joints temperature is comparitively low and at this low temperatures, this zone expereienced to induces a kind of ageing, hence it is resulted in a enhancement of mechanical properties. As a matter of fact, the microhardness map of GTAW+FSPed joints (shown in Figure 5) clearly indicates the lowest hardness values are related to the TMAZ region and stir zone, while the hardness of HAZ regions are slightly higher compared to the even un affected base metal.

The mechanical properties of both the welding processes of the joints are evaluated to understand the effect of FSP on GTAW Welds. Figure 5 shows the hardness distribution of the joints across the weld zone, and it is very clear that the hardness of the GTAW+FSPed joints are higher than the GTAW joints. The hardness values of the GTAW welds HAZ region exhibited higher hardness over the HAZ of the GTAW+FSPed joints. The recording of such a high hardness might

be due to the precipitates formation along the grain boudaries. As discussed in earlier section about the HAZ of the GTAW welds (see figure 3), the highest hardness is an evidence of precipitates induced in the HAZ and are significantly affect the weld strength. The equal hardness at the weld interface of both of the weld processes are suggesting that the FSP procedure greatly enhace the center region of the welds where the stirring effect on the GTAW fusion zone, and beyond that the properties are significantly not changed. As seen from the microstructures, the modified microstructures of the GTAW+FSPed welds of fine grain structure over the GTAW coarse grain structure, the hardness distribution directly indicates the evidence of improved microstructural charcteristics and mechanical properties of the GTAW+FSPed welds. The tensile strength of the joints also evaluated and are exhibited in figure 6. The strength of the both of GTAW and GTAW+FSPed welds are lower than the base metal strength. The strength of the GTAW welds and GTAW+FSPed welds is almost same with the slight variation in GTAW+FSPed welds. However, the GTAW+FSPed joints showed better performance and its elongation is higher than the GTAW welds. The slight increase of GTAW welds strength also may be due to the precipitates strength, while its strength is very less or negligible for GTAW+FSPed welds. Moreover, the ductility of the GTAW+FSPed welds are better than the GTAW welds due to the absence of porosities and other defects and improved microstructural charcteristics. The fracture surfaces of the welds also exhibited the joint failure occured in HAZ and TMAZ regions for the GTAW+FSPed joints, whereas the joint failure took place in the fusion zone for the GTAW welds with the larger voids formation. However, it is expecting that the strength of the GTAW+FSPed joints still can be improved further, if the induced stresses are released from the weldments by using any heat treatment techniques. It is also necessary to understand the details of the precipitates formation and its role on the welds by advanced characterisctic methods. The overal view of the microstructural characteristics and mechanical properties evaluation studies of this new approach resulted in improving the properties of the welds characteristics.

CONCLUSIONS

- A new approach of GTAW + FSP process was succesfully applied to the 2024 aluminum alloys to improve the weld metal properties.
- The defects and porosites formed in the GTAW welds are completely reduced by using FSP process.
- The FSP over the GTAW welds completely modified the microstructure and mechanical properties of the GTAW welds.
- The hardness of the GTAW+FSPed welds is higher than the GTAW welds due to formation of fine grain structure in the GTAW+FSP welds.
- The FSP has broken the precipitates and filled the gas pores by its stirring effect during FSP process and resulted in enhacing of weld metal characteristics, strength and ductility of the joints.

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